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An Experiment on Propagation of 60-GHz Waves Through Rain

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An experiment was designed to determine the effect of rainfall upon the attenuation and polarization of millimeter waves. Vertically polarized waves at 60 GHz were transmitted over a 1-km path, and the energy received in both the vertical and horizontal polarizations, as affected by rain, was detected and recorded at the receiving site; similarly, a horizontally polarized wave was transmitted and the same components measured. Data were collected over a period of one year (1970) using an all-solid-state measuring set. It was found that attenuation due to rain exceeded 42 dB for 5 minutes, and that a system employing orthogonally polarized signals would have had to tolerate signal-to-crosstalk ratios as poor as 22 dB for that same period of time.

I. INTRODUCTION

Crowding of the frequency spectrum is forcing designers of microwave communication systems to use higher frequencies and to give serious consideration to orthogonally polarized waves for increasing communication capacity. If adequate orthogonality can be maintained, the capacity of a system is double that of a system employing only one polarization. However, it has long been known that imperfections in antennas and other system components limit the degree of orthogonality that can be maintained in a practical system. Rainfall on the transmission path can also affect polarization and thereby limit the degree of discrimination against the unwanted signals at the receiver. The experiment described here was set up to determine the extent of such depolarization as well as the attentuation of 60-GHz waves.

The mechanism of attenuation and depolarization involves the geometry of raindrops. A number of workers have determined that large raindrops are seldom spherical and that they are capable of producing different amounts of attenuation for waves having different polarizations.[1,2] At the time our experiment was in the design stage,

Semplak[3] had already observed, at a frequency of 30.9 GHz, that attenuation for horizontally polarized waves was significantly greater than for vertically polarized waves during rainstorms. In this paper, we report data at about twice that frequency.

II. DESCRIPTION OF THE EXPERIMENT

The propagation path at Holmdel, New Jersey, is about 1.03 km long. The transmitting antenna is located on flat terrain about 30 feet above the ground and the receiver is on the southern slope of Crawford Hill. Propagation is along a path approximately 15 degrees west of true north. The transmitted carrier frequency is 60 GHz, near the maximum of the oxygen absorption line.[4] A horn-reflector antenna with 51-dB gain is employed at the transmitter and a horn-lens antenna with 53-dB gain at the receiver. The net clear-weather path attenuation is 39 dB, which includes a 15-dB loss due to oxygen absorption.

A single transmitter and receiver are employed. The polarization of the transmitted wave is switched from horizontal to vertical 10 times per second and the signal is gated on and off at a 20-Hz rate. The receiver is switched to respond five times per second, first to a horizontally polarized wave, and then to a vertically polarized wave. As a result of the switching we provide four separate outputs corresponding to the following conditions of polarization:

(*i*) Transmitter and receiver both horizontal, designated T_hR_h.
(*ii*) Transmitter and receiver both vertical, designated T_vR_v.
(*iii*) Transmitter horizontal and receiver vertical, T_hR_v.
(*iv*) Transmitter vertical and receiver horizontal, T_vR_h.*

Output signals corresponding to these four conditions are recorded separately and constitute our data. The effects we measure are the differences in the fading suffered by the various components during rainstorms.

The pulse output of each gate is detected and integrated, applied to a logarithmic amplifier, amplified, and recorded. It was not difficult to obtain a truly logarithmic output over an 80-dB range of input voltage, but it was difficult to obtain a truly linear detector output. By using one detector for the direct components and a separate one for the cross-polarized components, we are able to accommodate 50-dB fades with the recorded output a truly logarithmic function of the input over the complete range.

* In this nomenclature, for example, a cross-polarization discrimination is T_vR_v/T_vR_h and a crosstalk ratio is T_vR_v/T_hR_v.

III. EQUIPMENT

The fact tbat we are dealing with a narrowband measuring set in an application that requires a dynamic range of about 80 dB puts a premium on frequency stahility. A considerable part of our effort, therefore, was directed toward ohtaining such stahility.

3.1 Receiver

We chose to injection-lock the receiving local oscillator to a stahle 30-GHz signal obtained by harmonic generation from a 150-MHz source to obtain both a high degree of frequency stability and a low-noise output. To provide means for injecting the locking signal, the oscillator cavity shown in Fig. 1 was constructed. Tbe IMPATT diode is mounted at one end of thc center conductor of this coaxial cavity which is one wavelengtb long at 60 GHz. A prohe, one-quarter wavelength from the end, couples out 60-GHz energy into a section of the RG 98/U output waveguide. The 30-GHz energy is coupled from the RG 96/U injcction waveguide into tbe cavity at a point one-half wavelengtb (at 60 GHz) from tbe end of the cavity. Since this is at a potential null for the higher frequency, coupling can be accomplisbed witb minimum reaction to the 60-GHz signal. The 30- and 60-GHz waveguide sections are tuned hy means of sbort-circuiting plungers adjacent to the coupling probes. From an inspection of Fig. 1 it is evident that oscillation and locking could take place at 30 GHz and produce a 60-GHz output duc to the generation of second harmonic. Alternatively, 30-GHz oscillation could he suppressed by adjustment of the coupling probe, leaving the circuit free to oscillate at 60 GHz

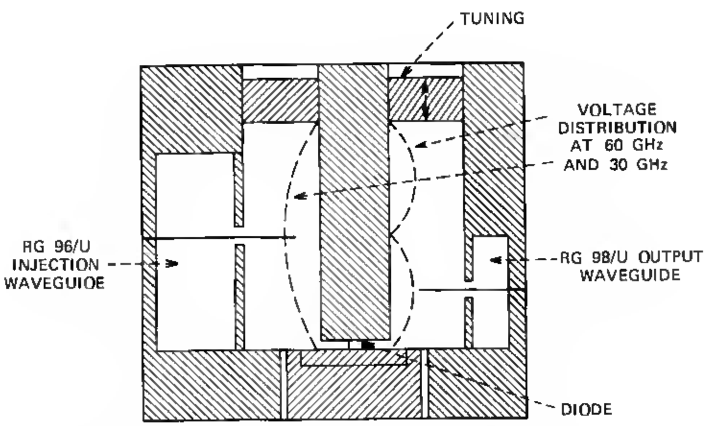

Fig. 1—60-GHz IMPATT oscillator. Diode is mounted at the end of the center conductor of the coaxial cavity.

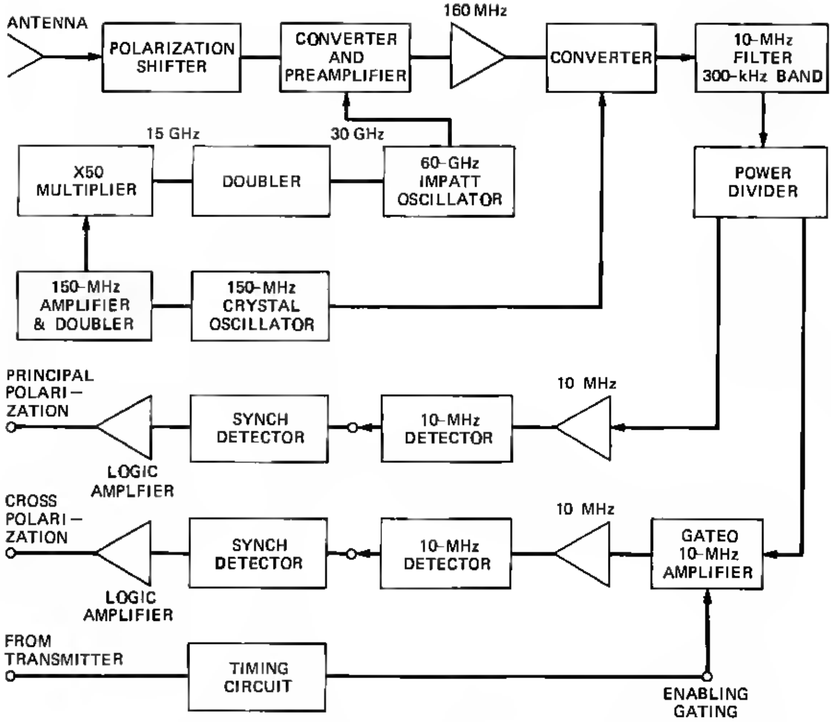

Fig. 2—60-GHz solid-state receiver with injection-locked local oscillator.

and lock on the second harmonic of the 30-GHz signal. The latter mode of operation proved most favorable.*

The IMPATT local oscillator in the receiver is locked to a signal generated from the output of the 150-MHz, crystal-controlled oscillator (see Fig. 2). A high-level 300-MHz voltage is applied to a step-recovery diode which has an output tuned to 15 GHz, thus providing a frequency multiplication of 50. The final locking signal, at a level of 0.2 mW, is obtained by doubling the 15-GHz signal in a diode harmonic generator. The locking range with this power level is known to be a few tens of MHz, which is sufficient to override cavity detuning due to temperature changes. Output power of the local oscillator of the receiver was about 4 mW.

For favorable adjustment, the FM noise output of the oscillator, when injection locked, was found to come largely from the injection

* In a preliminary experiment, 3 mW from a tunable Gunn oscillator was applied to the 30-GHz input to the oscillator, which delivered about 15 mW at 60 GHz. The IMPATT output frequency could be varied over a range of plus and minus a few hundred MHz by adjusting the frequency of the Gunn oscillator but leaving the IMPATT tuning fixed, resulting in a very satisfactory frequency lock.

signal. With a frequency multiplication of 400, this noise is 52 dB above that of the 150-MHz oscillator. However, the most frequently observed situation was one in which the IMPATT was noisy and the noise output was reduced by application of the locking signal. The cavity adjustments that resulted in stable, low-noise operation were obviously different from those that gave the widest frequency lock; the former condition was used in operation.

In the receiver the local-oscillator output is applied to a balanced converter where the incoming signal is translated to an intermediate frequency of 160 MHz. The converter employs wafer-type, silicon, point-contact rectifiers of the type described by Sharpless.[5] A transistor preamplifier with 10 dB of gain and a 2-dB noise figure is coupled directly to the converter. Although extensive measurements have not been made, there is evidence that local-oscillator noise is not limiting the performance of our system. The 160-MHz signal is mixed with 150 MHz in a second converter to provide a 10-MHz second intermediate frequency. After amplification, this IF signal is detected by linear detectors.

3.2 Transmitter

With only 0.2 mW of 30-GHz locking signal available, it was not possible to obtain the high output power needed from the transmitter and at the same time have a really satisfactory frequency lock. For this reason, the transmitter is controlled by an AFC circuit using a harmonically-generated 60-GHz signal as reference (see the block schematic in Fig. 3). With a feedback factor of nearly 1000, the transmitter output frequency is determined almost entirely by the crossover point of the 160-MHz discriminator and, therefore, is largely independent of changes in cavity tuning.

3.3 Performance

Before the system was installed in the field, the transmitter output was coupled to the receiver and the resultant 160-MHz IF signal monitored with a frequency counter. The frequency stayed within a few tens of kilohertz over a period of many days.

In the low-frequency section of the receiver, a logarithmic amplifier of the type described by Paterson,[6] simple and easily adjusted, provided a truly logarithmic output over a range of 80 dB. Obtaining a linear detector to drive this amplifier was more of a problem, but by amplifying the 10-MHz signal to a level of about 50 volts at the detector, a linear output was obtained over an input range of more than 50 dB. The required 80-dB dynamic range was obtained by dividing the incoming signal into two branches, one to recover low-

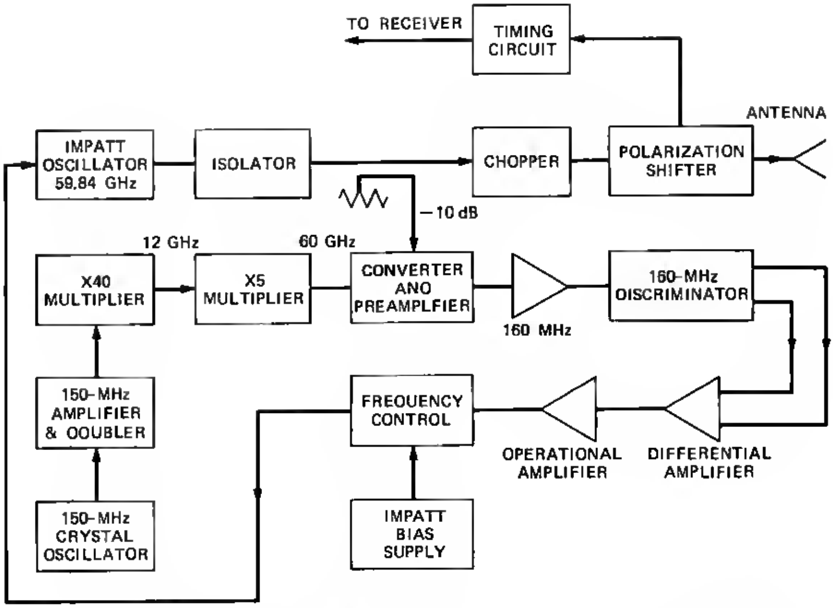

Fig. 3—60-GHz solid-state transmitter with frequency-controlled oscillator.

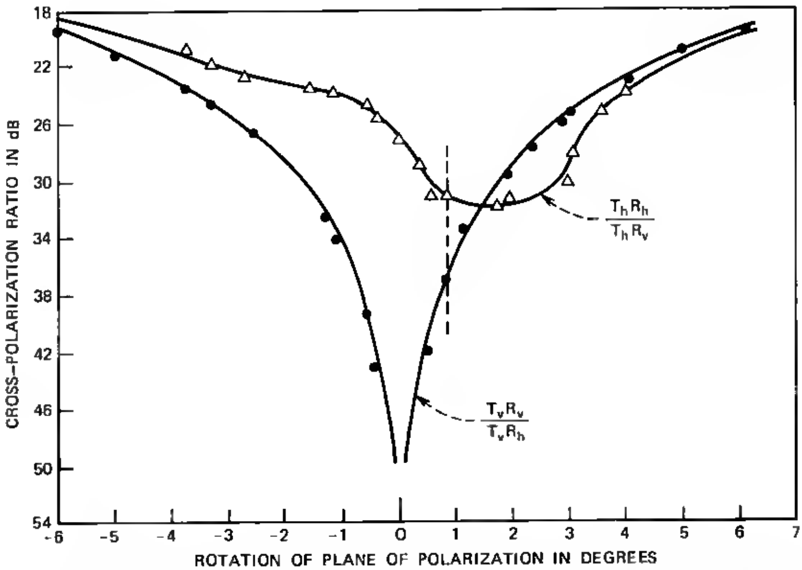

Fig. 4—Polarization discrimination characteristics of the operating system.

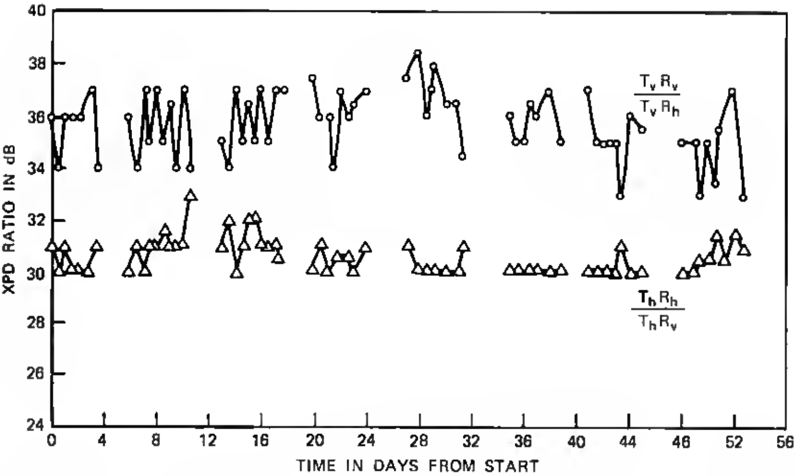

Fig. 5—Polarization discrimination with respect to stability. Not plotted for weekends.

level cross-polarization signals and the other to process the high-level signals.

3.4 Polarization discrimination and stability

After preliminary adjustments of the system on the path, a polarization shifter was placed in the receiver input to rotate the plane of polarization of the incoming waves and thereby determine the polarization discrimination of the system. The resultant outputs, plotted on Fig. 4, show that an excellent balance could be obtained for the condition T_vR_v/T_vR_h but, as a result of system imperfections in the antennas and other system components, the maximum discrimination for the condition T_hR_h/T_hR_v was only 32 dB, which indicates that slight elliptical polarization was present in the latter case. The system is normally adjusted to operate near the minimum of the horizontally cross-polarized component (see dashed line in Fig. 4), which at the same time provides more than 30 dB of discrimination against the vertically polarized component. Due to temperature or voltage changes, the operating point varied somewhat with time, as shown in Fig. 5. The gaps in the plotted data result from readings of stability not being taken during weekends.* Although no particular steps were taken toward stabilization, the discrimination ratio remained better than 30 dB over long periods of time without readjustment.

* This remark applies only to stability readings; all other data were accumulated continuously.

IV. EXPERIMENTAL RESULTS

4.1 Distribution of fades

Although the primary purpose of the experiment was to obtain data concerning polarization, it also yielded one year of information on the distrihution of rain fades. Figure 6 is a plot showing depth of fade versus the fraction of time this fading level was exceeded. We see, for this year, that for 60-GHz transmission over this 1-km path, a rain-fading margin of 40 to 42 dB would have heen needed to meet a reliahility ohjective of not more than 5 minutes of outage time (a prohahility of 10^{-5}). These data are found to be in good agreement with attenuations predicted from point rainfall rates.[7]

4.2 Polarization crosstalk distribution

The experimental results verify expectations that rainfall does degrade the polarization of 60-GHz waves, although much less than at lower frequencies.[2] The effect for this path is plotted in Fig. 7. The solid dots indicate crosstalk into the vertical channel (T_vR_v/T_hR_v), and the open circles indicate crosstalk into the horizontal channel (T_hR_h/T_vR_h). It is evident that, for our system, the polarization crosstalk ratio is 22 dB or more for 5 minutes during the year 1970.

Figure 8 shows data for a heavy rainstorm of July 31, 1970. This storm hehaved as expected in the sense that all quantities varied in

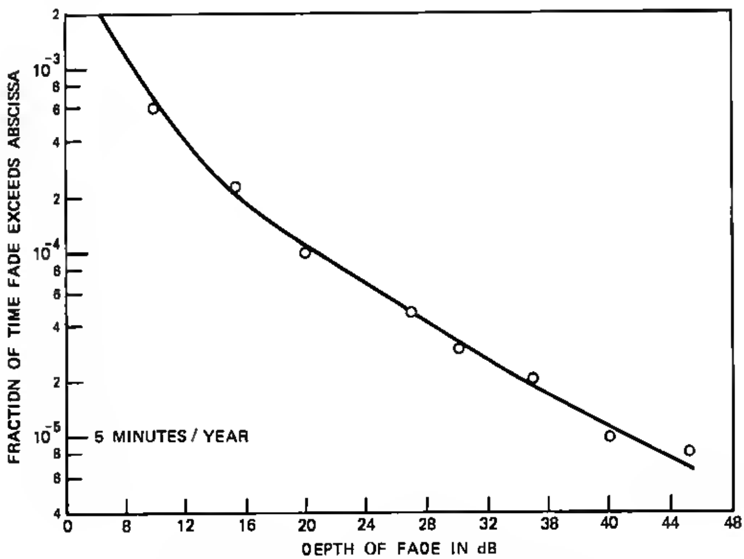

Fig. 6—Distribution of rain attenuation (1970).

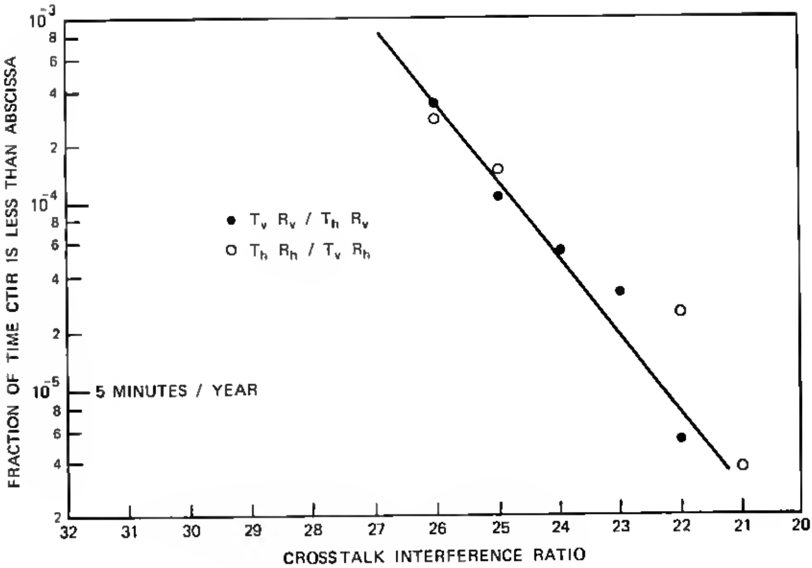

Fig. 7—Distribution of the crosstalk ratio.

the way one might expect from simple theory; i.e., differential attenuation was always positive (fade in horizontal polarization was greater than in vertical). The crosstalk variations were pretty much the same for both polarizations, with the ratio becoming poorer during the deeper fades.

On the other hand, the storm of November 4, 1970, plotted in Fig. 9, did not produce results expected from the simple theory. For a considerable portion of the time the differential attenuation was negative, indicating that attenuation of the vertical component was *greater than* that of the horizontal component. The fact that the crosstalk ratio in both channels (Fig. 9) improved slightly in this case may be explained by referring to Fig. 4, which shows the clear-weather operating point near +0.5 degree; a negative rotation (caused by the rain) of the vertical component from this value would reduce the cross-coupled energy and thereby improve the ratio. Similarly, a positive rotation of the horizontal component would improve the crosstalk ratio in that channel.

One expects differential attenuation at 60 GHz to increase with the absolute value of attenuation (much less than at lower frequencies).[2] This appears to be true on the average, as seen in Fig. 10. For fading levels greater than 25 dB, the differential appears to remain constant, but the limited amount of data available for very large fades makes de-

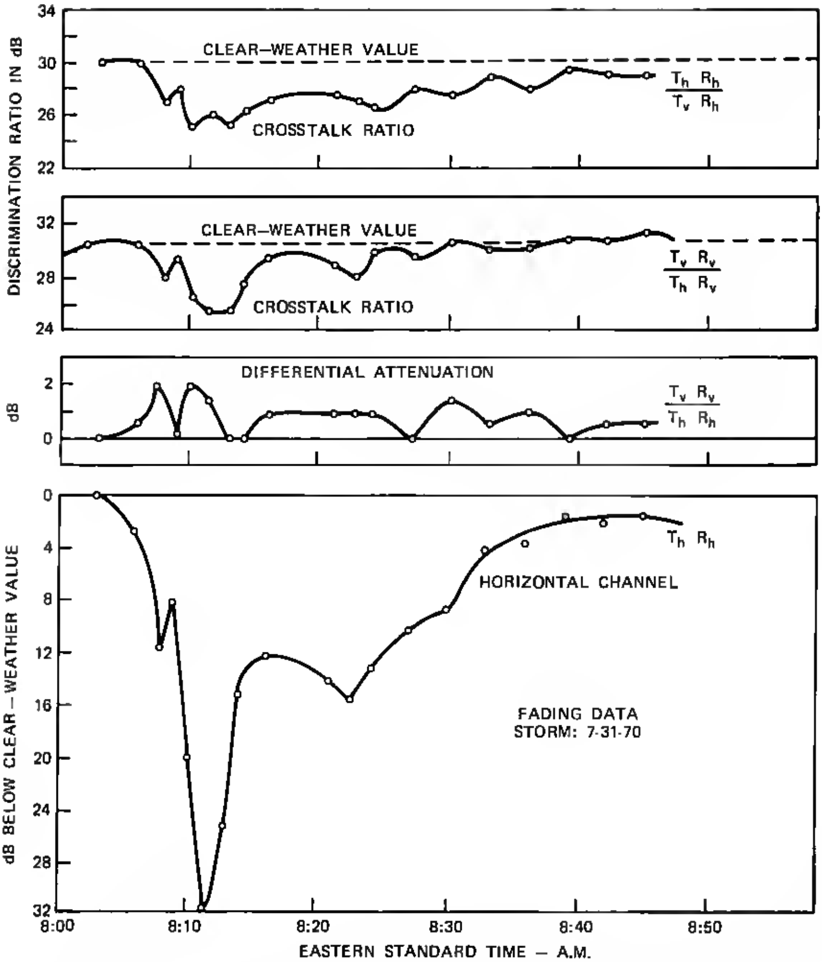

Fig. 8—Behavior of the various polarization components for the shower of July 31, 1970.

termination of the trend uncertain. The data points are very scattered, most likely due to variations of factors such as size, shape, and tilt of the raindrops involved. A number of negative differential attenuations are found for fades up to about 17 dB, but none above that value. The solid curve in Fig. 10 is drawn through the average value of the differential. A more significant quantity might be the maximum values, shown by the dashed curve; the maxima seldom exceed 2 dB, which is much less than the 6 dB observed[3] at 30 GHz for the same magnitude of fading.

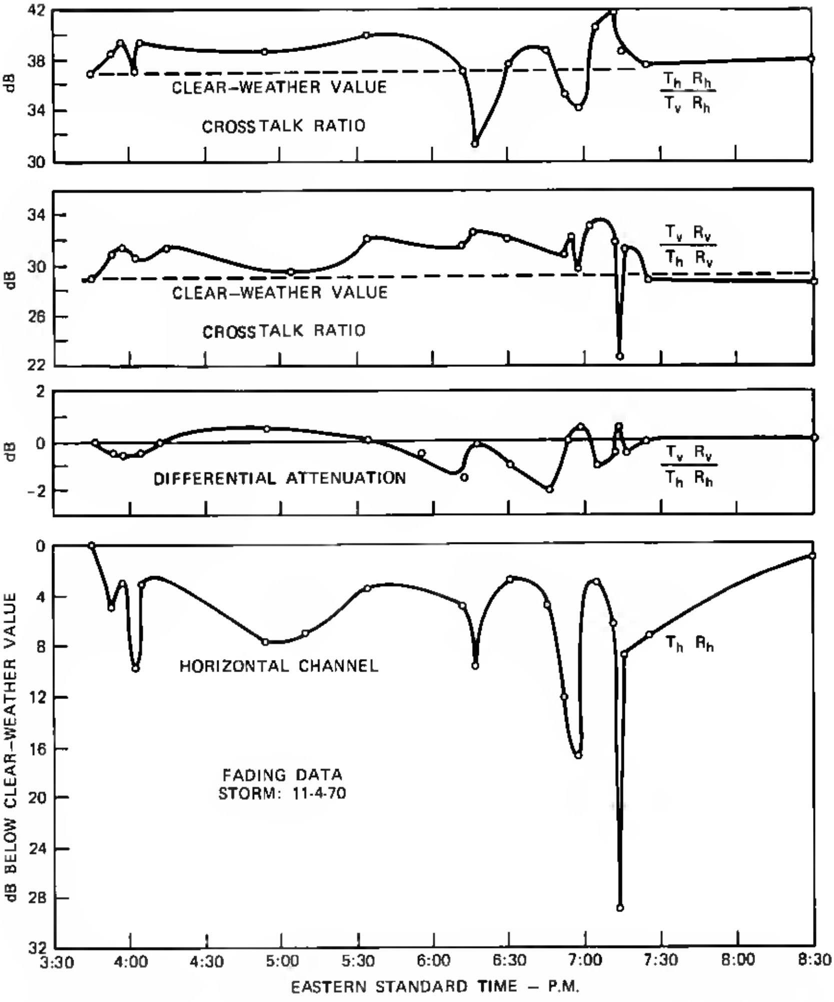

Fig. 9—Behavior of the various polarization components for the shower of November 4, 1970.

V. CONCLUSIONS

Consideration of propagation measured over a period of one year on a 1-km path in New Jersey, at a frequency of 60 GHz, leads to the following conclusions concerning this path and this frequency:

(*i*) Aside from polarization effects, a rain-fading margin of 40 to 42 dB would have been needed to meet a reliability objective of less than 5 minutes outage per year on a 1-km path.

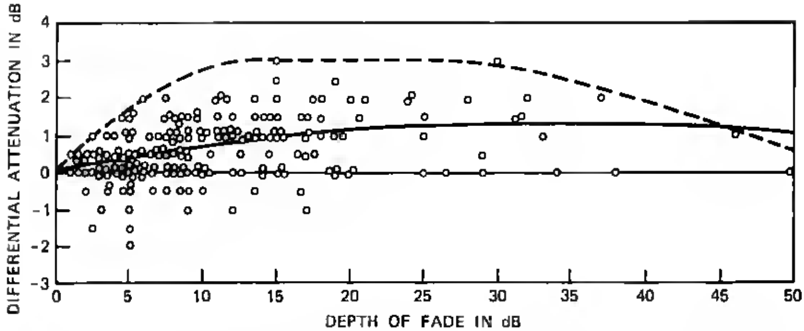

Fig. 10—Plot of measured differential attenuation as a function of fade depth.

(*ii*) The 60-GHz attenuation produced by rain is usually, but not always, greater for horizontally polarized than for vertically polarized waves; the differential is seldom greater than 2 dB and the average differential is only 1.25 dB, even for fades greater than 30 dB.

(*iii*) Rainstorms affect the polarization of 60-GHz waves transmitted through them, although not nearly as seriously for a given fade depth as at lower frequencies. A system accommodating a crosstalk interference ratio of 22 dB would operate satisfactorily over this path, suffering no additional outage over that resulting from attenuation.

VI. ACKNOWLEDGMENT

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